A Subarcsecond Companion to the T Tauri Star AS 353B[1]

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Received ________________________; accepted ________________________

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ABSTRACT

Adaptive optics imaging of the bright visual T Tauri binary AS 353 with the Subaru Telescope shows that it is a hierarchical triple system. The secondary component, located 5$''$.6 south of AS 353A, is resolved into a subarcsecond binary, AS 353Ba and Bb, separated by 0$''$.24. Resolved spectroscopy of the two close components shows that both have nearly identical spectral types of about M1.5. Whereas AS 353A and Ba show clear evidence for an infrared excess, AS 353Bb does not. We discuss the possible role of multiplicity in launching the large Herbig-Haro flow associated with AS 353A.

Subject headings: stars: formation – binaries: general – ISM: jets and outflows

1. INTRODUCTION

The T Tauri star AS 353A (HBC 292) was first recognized as an Hα emission object by Merrill & Burwell (1950) and Iriarte & Chavira (1956). AS 353A is particularly interesting, partly because it is one of the visually brightest known T Tauri stars ($V \sim 12.7$), but especially because it drives the prominent Herbig-Haro (HH) flow HH 32 (Herbig 1974; Herbig & Jones 1983; Mundt, Stocke, & Stockman 1983; Solf, Böhm & Raga 1986; Hartigan, Mundt, & Stocke 1986; Curiel et al. 1997). The optical spectrum of AS 353A is discussed in detail by Herbig & Jones (1983), Böhm & Raga (1987), and Eislöffel, Solf, & Böhm (1990), who find that it is heavily veiled with a rich emission-line spectrum and powerful Hα emission. Furthermore, AS 353A is detected in the radio continuum (Anglada et al. 1998), as is common for HH driving sources. The star displays considerable variability (e.g., Fernandez & Eiroa 1996), and is also known as V1352 Aql.

AS 353A has a fainter ($V \sim 14.6$) companion star, AS 353B (HBC 685), about 5$''$.6 to

the south. In marked contrast with the many studies of the A-component, this companion has been only poorly studied. It is a weak-line T Tauri star with a spectral type estimated to be M0 by Cohen & Kuhi (1979) and M3 by Prato, Greene, & Simon (2003). Both stars are located in a cloud cavity, whose edges are illuminated by the two stars, as seen well in the *Hubble Space Telescope* images of the region by Curiel et al. (1997).

In this paper, we present near-infrared adaptive optics observations of the AS 353A/B pair. Our motivation for undertaking these observations was to search for a companion to AS 353A. We were unsuccessful in this, but we found AS 353B to be a subarcsecond binary (independently discovered by White et al. 2002).

2. OBSERVATIONS

Diffraction-limited imaging of AS 353 A and B was obtained with the Infrared Camera and Spectrograph (IRCS) instrument at the Subaru Telescope (Tokunaga et al. 1998; Kobayashi et al. 2000) on 2001 July 12 UT. The IRCS was used with the Subaru Telescope adaptive optics system (Takami et al. 1998; Gaessler et al. 2002) using AS 353A as the reference star for the wavefront sensor. Images were taken at H (1.63 μm), K (2.19 μm), and L' (3.72 μm) with the isophotal wavelengths are given in parentheses. The pixel scale was 22.560 $\pm$ 0.059 milliarcsec pixel^{-1}. The Mauna Kea Observatories near-infrared filters described by Simons & Tokunaga (2002) and Tokunaga, Simons, & Vacca (2002) were used. The observations were made with a box-shaped five-image dither pattern with a separation of $2''\!.0$. The total integration time for the H, K, and L' images were 100, 75, and 180 s, respectively.

Although our objective was to determine if AS 353A is a binary star, we instead discovered that AS 353B is a binary. There is no evidence in our images that AS 353A has

a companion with a separation greater than $0''.1$. Figure 1 shows the L' image of the AS 353 system.

The Strehl ratio was estimated from the ratio of the peak flux to that of the total flux and comparing these values to a theoretical diffraction-limited image. The Strehl ratio was found to be 0.09 at H, 0.21 at K, and 0.51 at L'.

The images were reduced using IDL procedures. Aperture photometry was performed on AS 353A with a radius of $1''.6$. The conversion from ADU s^{-1} to magnitudes was determined from the zero point magnitude derived previously since a photometric standard was not observed due to time limitations. The airmass during the observations ranged from 1.16 to 1.28. The sky conditions were good, and the atmospheric extinction coefficients from Krisciunas et al. (1987) were adopted. Relative photometry of the components of A, Ba, and Bb was obtained using an aperture radius of 5 pixels ($0''.11$). The magnitudes for AS 353Ba and Bb were then obtained from that of AS 353A, and the photometric results are shown in Table 1.

The uncertainties in Table 1 were obtained from the variations in the photometric counts from frame to frame. Additional systematic uncertainties arise from the use of the photometric standard of another night and the adopted zero magnitudes based on the available photometric observations. The systematic uncertainties are approximately 0.05 mag.

We obtained spectroscopic observations of AS 353Ba and Bb in the H and K bands on 2002 May 26 UT using the IRCS in the grism mode with a $0''.15$ slit. The resolving power was 610 and 640 at H and K, respectively. As with the imaging, the Subaru adaptive optics system was used, and the slit was aligned along the Ba and Bb components. The object was nodded along the slit by $3''.0$ in two positions. A set of four spectra (two in the positive beam and two in the negative beam) was obtained at both the H and K bands.

The total integration time was 120 s at H and 240 s at K. The spectra were reduced using IDL routines and the "optspec" procedure provided by M. Buie.[8]

The A0 star HD 189411 was used to correct for telluric absorption. The typical method of obtaining the spectrum of an object is to divide by the telluric standard and multiply by a Planck function that approximates the continuum of the standard. However, we employed an alternative method described by Vacca, Cushing, & Rayner (2003) of using the known spectral type of the telluric standard and the measurement of at least one of its absorption lines to model both the continuum and line absorption. The instrumental profile and atmospheric absorption can then be derived, and these are used to obtain the spectrum of AS 353Ba and Bb. The primary advantage of this method is that the spectral lines in the telluric standard are removed to a greater degree than is possible by other methods. The resulting spectra are shown in Figure 2.

3. DISCUSSION

3.1. The AS353B Binary

Figure 1 shows the L' image of AS 353A/B, and it is apparent that AS 353B is resolved into a subarcsecond binary, where we denote the brighter component as Ba and the fainter as Bb. It has a separation of $0\farcs24 \pm 0\farcs01$ with a position angle of $107\fdg2 \pm 1\fdg3$ as measured from AS 353Ba. The separation of AS 353A and Ba is $5\farcs63 \pm 0\farcs01$ with a position angle of $174\fdg1 \pm 0\fdg2$ as measured from AS 353A. The uncertainties in separation are derived from the standard deviation of the individual frames. The uncertainty in the position angle does not include the uncertainty in mounting the instrument onto the telescope (estimated to be $\pm$ $0\fdg1$). These values improve upon those of Chelli, Cruz-Gonzalez, & Reipurth

[8]http://www.lowell.edu/users/buie/idl/idl.html

(1995), since the A–B separation is more precisely measured now that we have resolved the components of AS 353Ba and Bb.

The spectral type of AS 353A is K2 (Basri & Batalha 1990). Prato et al. (2003) show a spectrum of AS 353A in which He I and strong Brγ emission is seen. The spectrum of AS 353Ba and Bb combined is M0–M3 (Cohen & Kuhi 1979; Prato et al. 2003), and as can be seen in Figure 2, the spectra of AS353 Ba and Bb are very similar. We compare the spectrum of AS353 Ba to the standard star spectra of Wallace & Hinkle (1997) and Meyer et al. (1998) in Figures 3 and 4, respectively. For this comparison, we have converted to F_λ (W m^{-2} μm^{-1}) and wavelength units, and smoothed the spectra to match that of our AS 353Ba spectrum.

Figure 3 shows that in the K band the spectrum of AS 353Ba resembles that of an M dwarf star since the CO absorption at 2.3–2.4 μm is too strong in the spectra of the giants. The Mg I line at 2.28 μm is a good indicator of the spectral type. We see that this line is nearly absent by spectral type M2V. K-band spectra obtained by J. Rayner (2003, private communication) show that AS 353Ba is similar to a M1.5V main-sequence star but not later. This conclusion is also consistent with comparison to the spectral standards shown by Ali et al. (1995). Our spectral type estimate is a little earlier but consistent with the spectral type of M3 $\pm$ 2 obtained by Prato et al. (2003).

Figure 4 shows that the spectrum of AS 353Ba is not a good match to the spectra of either dwarf or giant stars. The Mg I (1.58 μm) and CO band (1.62 μm) are best matched to a giant spectrum earlier than M1. However the Mg I (1.71 μm) line is best matched to a dwarf spectrum of M1.5V or later. Thus the H-band spectrum shows spectral characteristics of both dwarfs and giants. Evidence that premain-sequence stars show spectral characteristics intermediate between dwarfs and giants has also been presented by Luhman (1999).

The straight continuum at 2.0–2.5 μm is also an indication of an early M spectral type. Comparison of the continuum shapes to the M dwarf spectral library of Leggett et al. (2002)[9] indicates that the spectral type is about M1 or later. Therefore, our best estimate is that the spectral types of both AS 353Ba and Bb are about M1.5.

The $H - K$ and $K - L'$ colors can be used to roughly classify the objects in terms of infrared excess, extinction, and spectral type. In Figure 5 we show the position of AS 353A, Ba, and Bb in a color-color diagram. We see that AS 353A and Ba have infrared excesses and follow the classical T Tauri line derived by Meyer, Calvet, & Hillenbrand (1997). The difference in brightness between Ba and Bb may result from the infrared excess of component Ba, or alternatively from variability.

Our magnitudes for AS 353A at H and K are within ± 0.3 of those presented by Cohen & Schwartz (1983) and by Prato et al. (2003), and our L' magnitude is 0.1 brighter than found by Cohen & Schwartz (1983). We note that Fernandez & Eiroa (1996) show that the visual magnitude of the AS 353 system (A, Ba, and Bb) varies by ± 0.5 mag. The combined magnitude of Ba and Bb are within ≤ 0.07 mag of that reported by Cohen & Schwartz (1983) and within 0.3 mag of Prato et al. (2003). The $H - K$ color of AS 353A and AS 353B (combined) are within 0.05 and 0.1 mag, respectively, of the colors derived from the data of Cohen & Schwartz (1983) and by Prato et al. (2003).

AS 353Bb has colors similar to that of an M0 star. Combined with the spectral type of AS 353Bb obtained above, we infer that the extinction of AS 353Bb is nearly zero in the near infrared. Note that Prato et al. (2003) obtained a visual extinction of 2.1 ± 0.8 for the combined light from Ba and Bb. However, if we apply such a correction to AS 353Bb, the resulting colors would be inconsistent with the early M spectral type found above. Thus

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[9]Spectra available at anonymous ftp site: ftp.jach.hawaii.edu, cd /pub/ukirt/skl.

the visual extinction value obtained most likely pertains to Ba, the brighter component.

Cohen & Kuhi (1979) reported that the Hα equivalent widths for AS 353A and AS 353B (combined) were 124 Å and 4.4 Å respectively. AS 353A is redder and has more thermal emission than the binary companion, and within the binary system, AS 353Ba has detectable thermal emission but AS 353Bb does not. Coupled with the Hα emission, this is evidence for emission from an accretion disk in both AS 353A and AS 353Ba.

AS 353A is clearly the most active member of the system, since the outflow is emanating from this component and it has strong emission lines. Duchêne et al. (1999) found evidence that, in binary systems where both stars are still accreting material, the more massive star has the larger accretion rate as measured by the Hα luminosity. This is consistent with the picture that AS 353A is the most massive object in the system and that it has a very red $K - L'$ color due to an accretion disk. The AS 353 system fits the trend reported by Duchêne et al. (1999) that the more massive object has the higher accretion rate in binaries.

The distance to AS353 is uncertain. Herbig & Jones (1983) estimated the distance to be 300 pc, but they emphasized the uncertainty of this determination and noted that their astrometric distance methods tend to overestimate the derived distances. Prato et al. (2003) adopt a distance of 150 $\pm$ 50 pc following the estimated distances of Edwards & Snell (1982) and Dame & Thaddeus (1985), who obtained distances of $\geq$150 pc and 200 $\pm$ 100 pc, respectively. However, the Edwards & Snell distance estimate does not take into account the now-known binarity of AS 353B, and they also assume that the AS 353B component is a single main-sequence star. The Dame & Thaddeus distance estimate is for that of the Aquila Rift. They note that the distance estimates range from 150 pc near $\ell = 20°$ to $\sim$300 pc near $\ell = 40°$. Since AS 353A is at $\ell = 46.5°$ and the visual extinction is about 2.1–2.9 (Prato et al. 2003; Cohen & Kuhi 1979), it is likely that AS 353A is in the

foreground to the Aquila Rift and at a distance of ≤ 300 pc. Prato et al. (2003) find that a distance of 150 pc gives a reasonable age for the AS353B component, and this is the best estimate of the distance at this time.

For a distance of 150 pc, the absolute K magnitude of AS 353Ba and Bb separately is approximately 3.2 mag. This is about 2.6 mag brighter than the absolute magnitude of a main-sequence M2V star.

The projected separation between AS 353Ba and Bb is only 36 AU. It is interesting to note that Jensen, Mathieu, & Fuller (1996) find that binaries with separations between a few and about 100 AU have low submillimeter continuum emission. This suggests to them that such binaries do not have circumbinary disks. The large $K - L'$ color for AS 353A and small $K - L'$ for AS 353B is consistent with the results of Jensen et al. (1996). In addition, White et al. (2002) find that close binaries in triple systems are always the nonaccreting component. In the case of AS 353, there is some accretion in AS 353Ba, but it is small in comparison to AS 353A.

3.2. An Evolutionary Scenario

AS 353A is associated with the well-known HH 32 flow[10]. In the last few years, it has been recognized that HH flows may commonly attain very large, parsec-scale dimensions (e.g., Reipurth, Bally, & Devine 1997; Gómez, Kenyon, & Whitney 1997). Such giant HH flows provide a fossil record of the mass-loss activity and accretion history of their driving sources. Detailed studies of 14 sources of giant HH flows have revealed an *observed* binary frequency of about 80%, of which half are higher order multiples, leading Reipurth (2000) to postulate the stellar dynamics jet hypothesis, in which dynamical decay of triple or multiple systems leads to strong outflow activity that manifests itself in the multiple shock structures observed in giant HH flows.

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[10]The HH 32 flow has an inclination of about 70° with respect to the plane of the sky, and so is significantly foreshortened (e.g., Herbig & Jones 1983; Curiel et al. 1997). A faint group of HH knots, HH 332, is found 68″ SSW of AS 353A (Davis, Eislöffel, & Smith 1996), and it could well be the fading remnants of a terminal working surface of the HH 32 flow. However, there is an approximately 40° angle between lines from AS 353A to HH 32 and HH 332, which is a substantial difference, even considering that HH flow axes are known to vary with time. But when we take into account the 70° inclination of the HH 32 flow, the angle between the actual directions from AS 353A to HH 32 and HH 332 reduces to about 13° degrees, which is commonly seen in giant HH flows. If this is so, the physical length of the HH 32/HH 332 large-scale flow, assuming a distance of 150 pc, is 30,000 AU, or 0.15 pc. While this would in itself not be considered a giant flow, it does indicate that the HH 32 flow may be much larger than its currently recognized extent would suggest. Since HH 32 is a redshifted HH object, a prediction of the connection with HH 332 would be that this HH flow should also be redshifted. In contrast, the large majority of HH flows are blueshifted, due to selection effects related to dust obscuration.

The stellar dynamics jet hypothesis predicts that the HH 32 source should be part of a triple or multiple system that has recently gone from a nonhierarchical configuration to a hierarchical one. Our observations indeed show AS 353A/B to be a hierarchical triple system. However, since the HH 32 flow unquestionably arises in AS 353A, and not in AS 353B, we would expect AS 353A to be a binary as well.

We thus speculate that the AS 353 AB system is not only a triple system, as observed, but also a quadruple, with AS 353A being an unresolved close binary. If so, this would make it very similar to UZ Tau, where one component is a close visual binary (Simon et al. 1992) and the other is a spectroscopic binary (Prato et al. 2002). This configuration can arise from an initial nonhierarchical quadruple system. Such systems are unstable, and subsequent dynamical interactions would transform this system within about a hundred crossing times (Anosova 1986; Sterzik & Durisen 1995). This can occur in one of several ways. Ejections can lead to (1) the escape of two stars; (2) one star escaping and another placed in a distant orbit; (3) a binary being placed in a distant orbit. In all such scenarios, the most massive member remains a binary that becomes tighter by the ejection process. The members that either escape or are placed into a distant orbit will likely have some of their disks truncated in the process, or at least will be displaced from the center of the potential well, leading to less accretion. In either case the outlying component(s) should have less circumstellar material than the inner dominant binary (e.g., Bate & Bonnell 1997; Bonnell et al. 2001; Bate, Bonnell, & Bromm 2002).

It is tempting to interpret AS 353, and other premain-sequence binaries like UZ Tau, in terms of case 3. If this is so, then AS 353A itself should be a close binary surrounded by substantial amounts of circumstellar material. Figure 5 shows that AS 353A has a very substantial infrared excess, in contrast to the Ba and Bb components. Binary motion in such a viscous environment may lead to rapid spiraling-in of the components, suggesting

that at present the binary would be much closer than the Ba/Bb pair, consistent with our upper limit of $0\farcs1$ (15 AU in projection) for the presence of any companion.

4. CONCLUSIONS

1. Adaptive optics imaging of AS 353A reveals that its companion $5\farcs63$ to the south is a close binary system with a separation of $0\farcs24$. AS 353A itself did not show any companion with a projected separation larger than $0\farcs1$. Thus the AS 353 system is a hierarchical triple system.

2. The components of the close binary system, AS 353Ba and Bb, have nearly identical spectral types of approximately M1.5. At an assumed distance of 150 pc, the absolute K magnitude of Ba and Bb places them well above the main sequence. The spectra of Ba and Bb have spectral characteristics of both dwarfs and giants.

3. AS 353A and Ba show infrared excesses that are typical for T Tauri stars, but AS 353Bb does not. The infrared colors and spectra of AS 353Bb show that the extinction to this source is nearly zero.

4. We suggest that the present AS 353 system evolved dynamically from an unstable nonhierarchical quadruple system and predict that AS 353A is a close binary.

We thank the staff and crew of the Subaru Telescope for their invaluable assistance in obtaining the observations reported here. We are grateful to J. Rayner and S. Leggett, who made available their M dwarf spectral libraries to us, and to W. Vacca and M. Cushing for providing their version of the 'xtellcor' program prior to publication. We thank G. Herbig for helpful comments on the spectrum of AS 353A. ATT was supported by NASA Cooperative Agreement no. NCC 5-538.

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This manuscript was prepared with the AAS LaTeX macros v5.0.

Table 1: Magnitudes for the AS353 System[a]

Object	K	$H-K$	$K-L'$
AS353A	7.97	0.93	1.73
AS353Ba	9.26	0.35	0.56
AS353Bb	9.45	0.26	0.13

(a) The 1 σ uncertainties for H, K, and L' are 0.03, 0.03, and 0.06 mags, respectively.

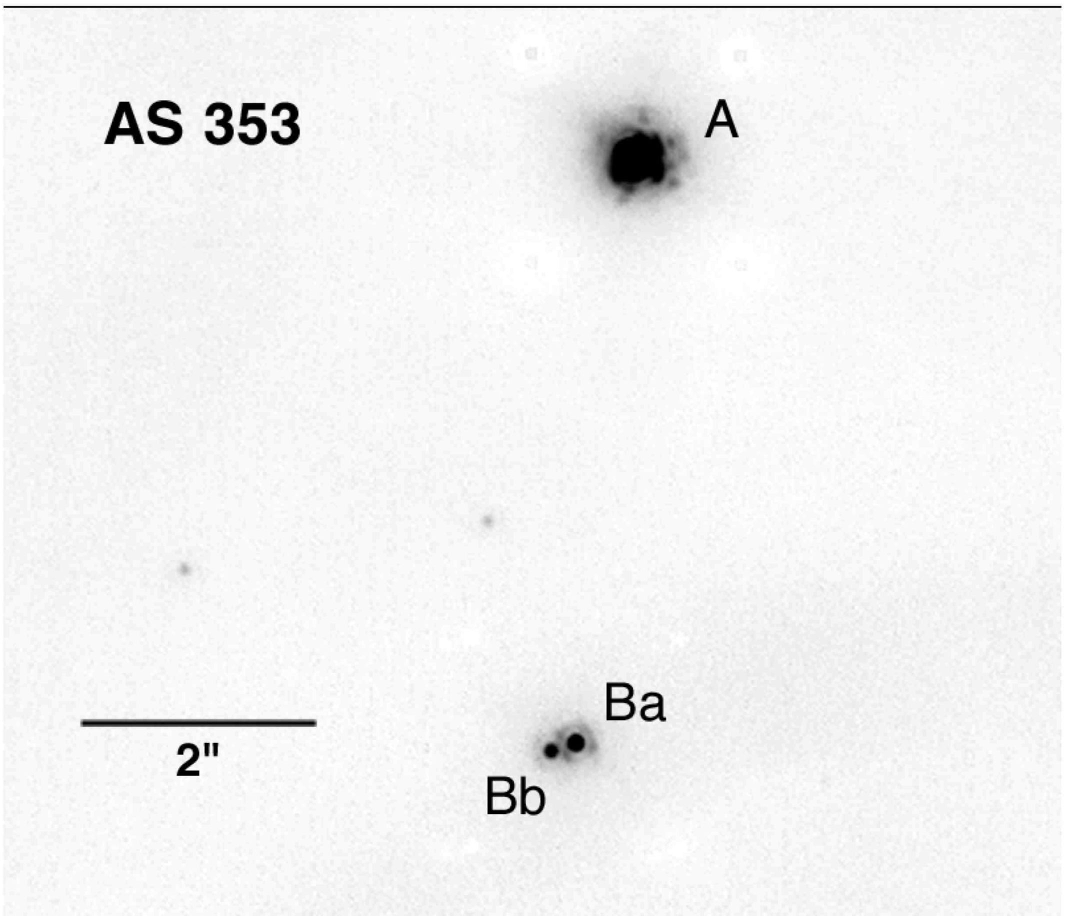

Fig. 1.— L' image of AS 353A, Ba, and Bb obtained at the Subaru Telescope with IRCS and the Subaru adaptive optics system. North is up and East to the left. Structure in the wings of the point-spread function of AS 353A is speckle noise. Since the integration time was short, no extended structure in AS 353A was observed.

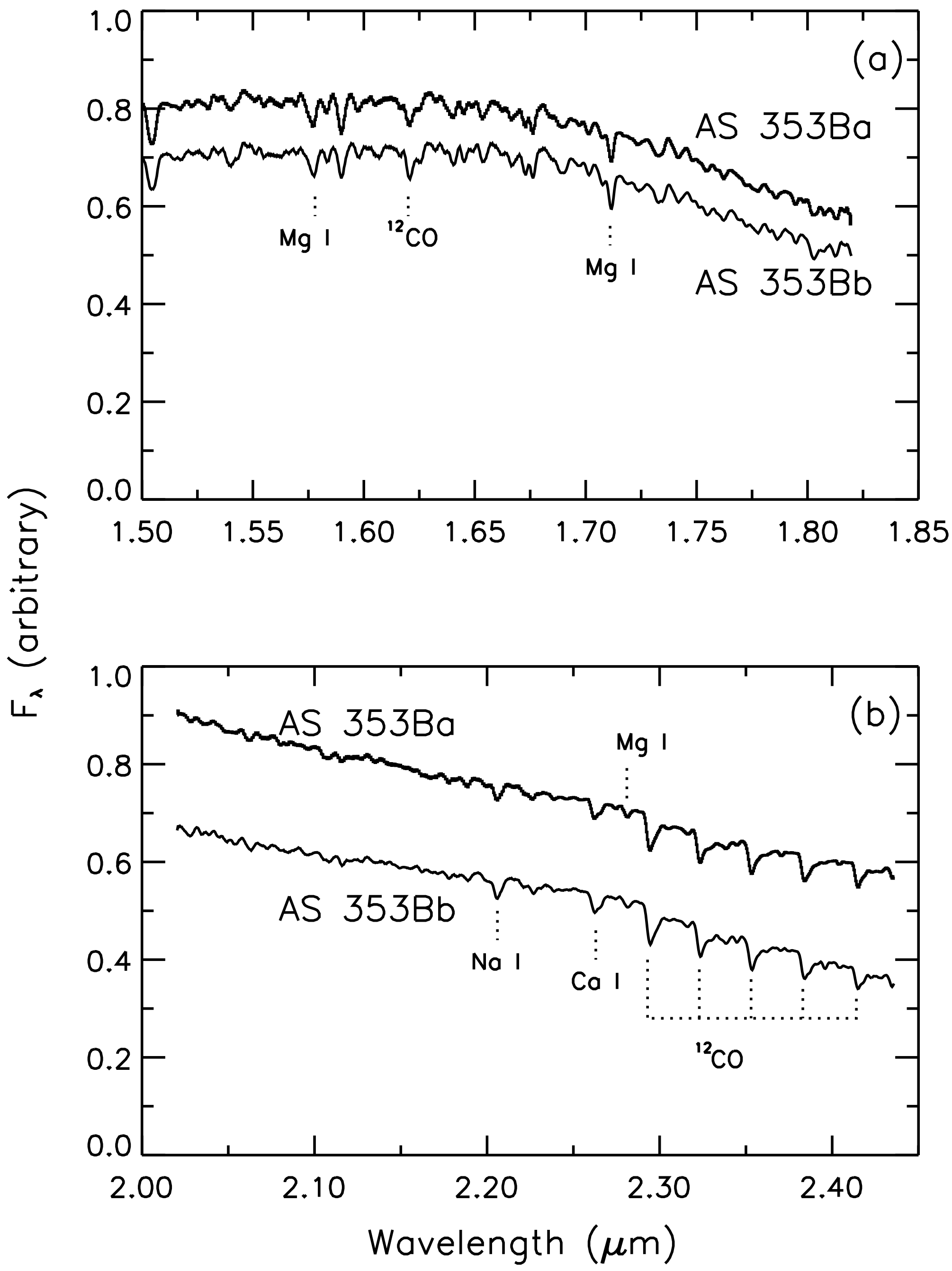

Fig. 2.— Grism spectra of AS 353Ba and Bb. (a) The *H*-band spectra of AS 353Ba (upper curve) and AS 353Bb (lower curve). (b) Same as above for the *K* band.

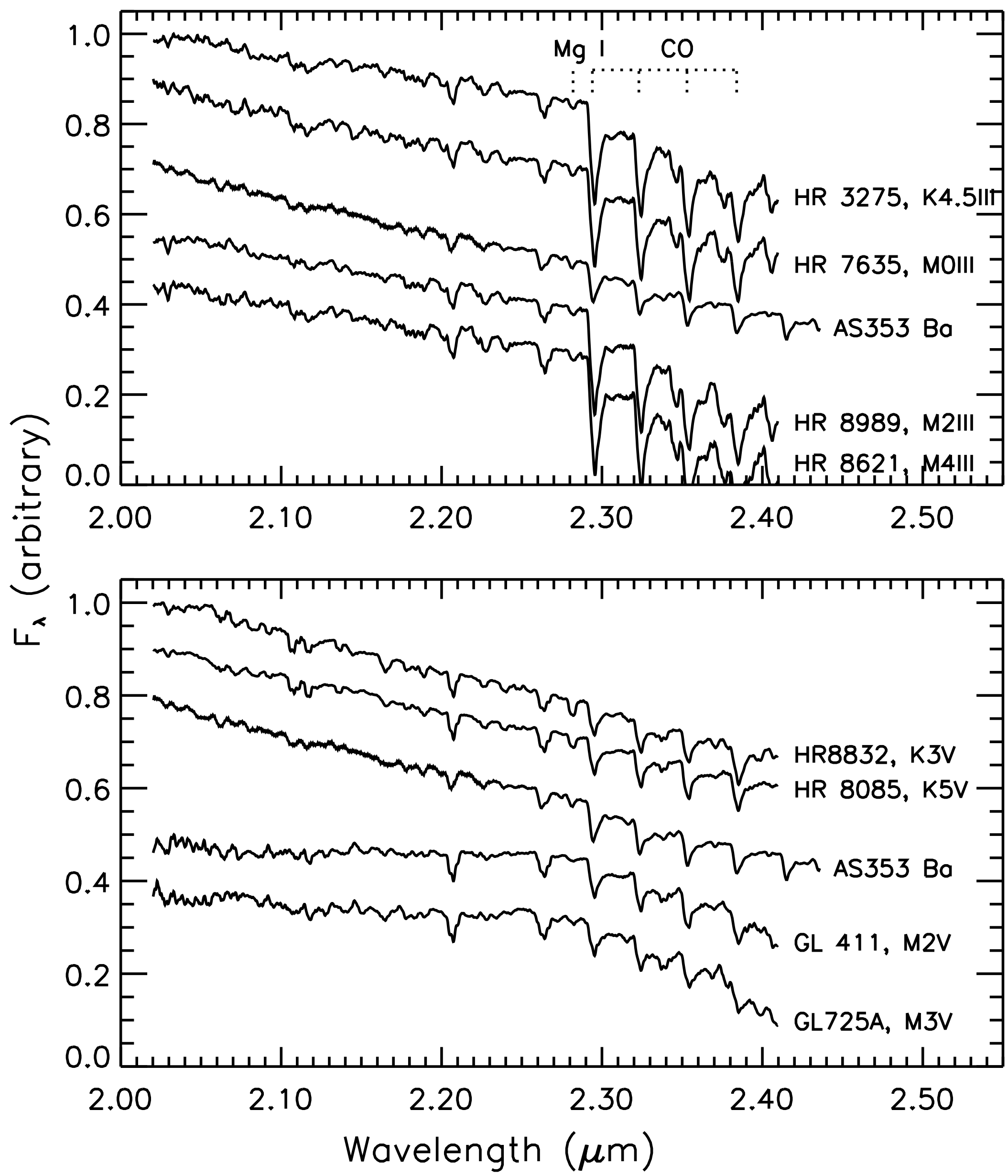

Fig. 3.— Comparison of AS 353Ba with spectral standards from Wallace & Hinkle (1997). The comparison to giant main-sequence stars is shown in the top panel, and to dwarf stars in the bottom panel. The Mg I line at 2.28 μm and the ^{12}CO bandheads are shown.

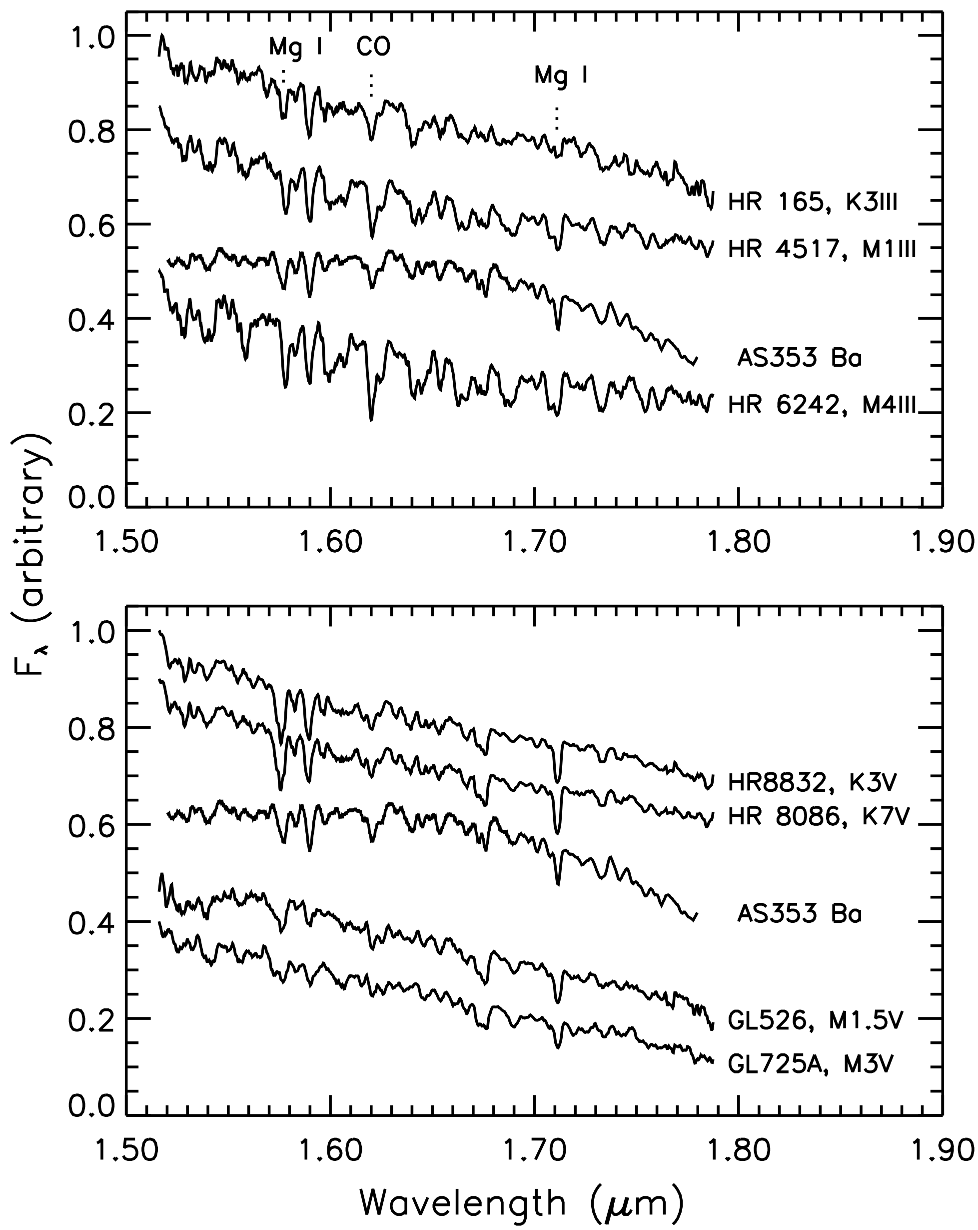

Fig. 4.— Comparison of AS 353Ba with spectral standards from Meyer et al. (1998). The comparison to giant main-sequence stars is shown in the top panel, and to dwarf stars in the bottom panel. The Mg I lines at 1.58 and 1.71 μm and the ^{12}CO band at 1.62 μm are shown. The continua in the Meyer et al. spectra were apparently flattened.

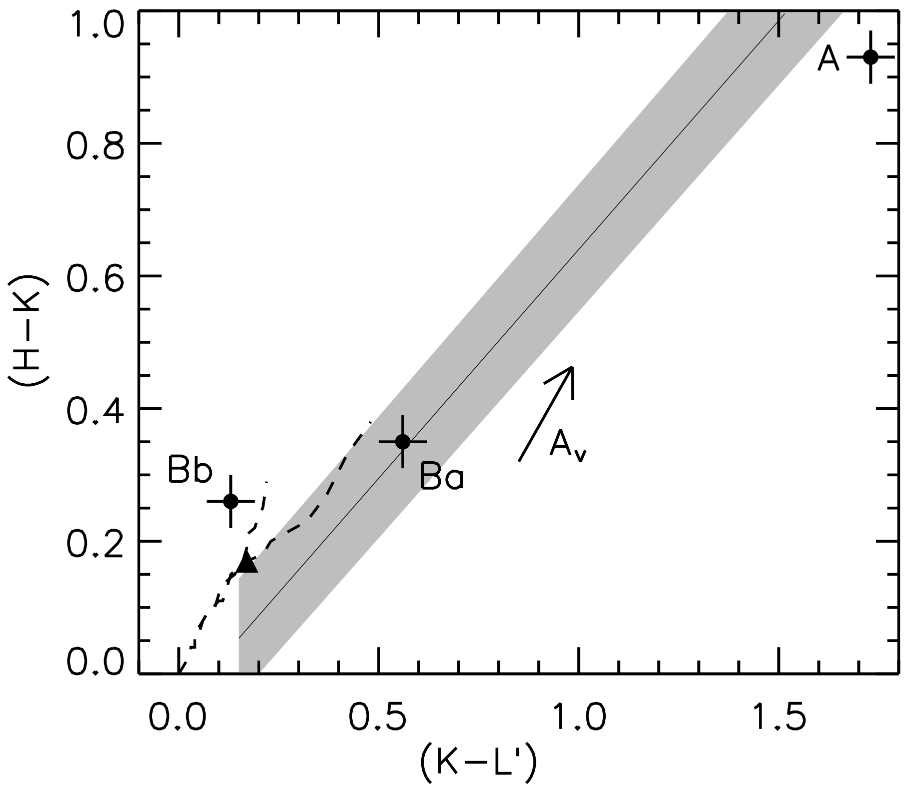

Fig. 5.— AS 353A, Ba, and Bb placed in a color-color diagram showing the main-sequence colors of dwarfs and giants (dashed lines) and the dereddened classical T Tauri star locus (solid line) from Meyer et al. (1997). The triangle symbol shows the location of an M0 main-sequence star. The shaded area shows the approximate width of the scatter about the classical T Tauri star locus. The arrow shows the reddening vector for $A_V = 2.1$ in the direction of increasing extinction.